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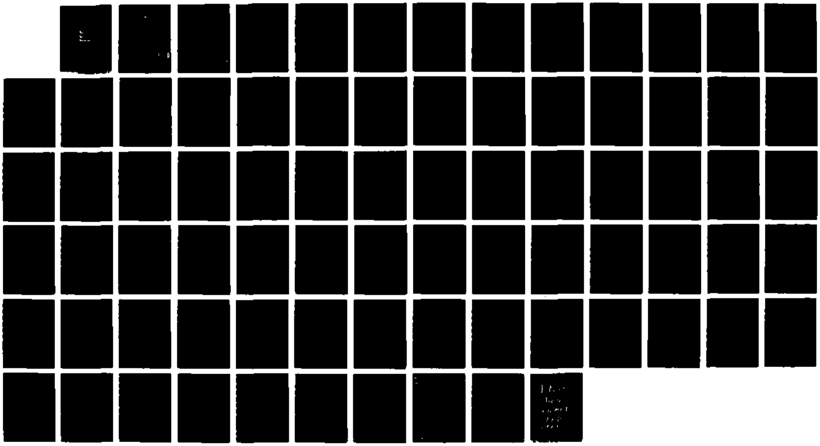

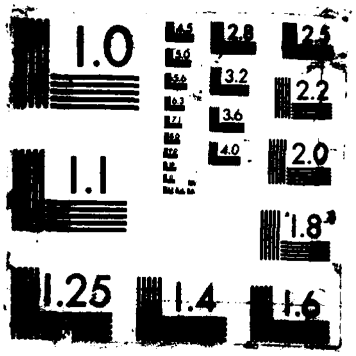
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AIR FORCE INSTITUTE OF TECHNOLOGY (AFIT) LOCAL AREA NETWORK (LAN) PERFORMANCE EVALUATION MODEL: AN ANALYTIC MODEL FOR ASSESSING THE IMPACT OF CHANGING LAN HARDWARE AND SOFTWARE CONFIGURATIONS

THESIS

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THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Systems Management

Alan B. Tucker, Jr., B.A.

Captain, USAF

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Preface

The purpose of this study was to develop an analytic model for evaluating the performance of the Air Force Institute of Technology's (AFIT) local area network. Although the analysis is specifically tailored for AFIT's Carrier Sense Multiple Access with Collision Detection (CSMA/CD) broadband network, the approach could be used to evaluate other CSMA/CD based networks.

The modeling analysis indicates the network will meet AFIT's expanding networking requirements. The capacity of the system should allow for several channels to be set aside for future experimentation and modeling efforts. With the Air Force's growing dependence on networks and the rapid technological advances taking place in the field, more research in this area is certainly warranted.

In conducting the network experimentation and writing this thesis I have had a great deal of help from others. I would like to thank Mr. Bill Nucefora of Mitre Corporation for providing much needed documentation and technical advice. I also wish to thank my thesis advisor, Professor Meadows, for his guidance and encouragement throughout this effort. Lastly, I am deeply indebted to Mr. Jim Mulder and his staff in the HQ AFLC LAN project office. Their eager cooperation and the liberal use of their network resources made this thesis possible. I wish them the best of luck in the future.

Alan B. Tucker, Jr.

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Abstract

The purpose of this study was to develop a performance evaluation model to analyze the impact of changing hardware and software configurations on a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) based local area network (LAN). The analysis focuses on the specific network software and computing equipment used on the Air Force Institute of Technology (AFIT) LAN.

The analysis was accomplished in two parts. First, a functional model of the network was prepared using available technical documentation and by consultating with system experts. The second part of the process was performance modeling. Individual traffic loading models were developed for each device to be connected to the AFIT LAN. Packet sizes characteristic of the networking software and access method were then specified for each device, and an aggregate data rate for each device was computed. Three performance measures: maximum channel efficiency, throughput, and minimum average delay were then selected to evaluate overall network performance. A standard spreadsheet program was used to construct the model. The results of the modeling analysis indicate the AFIT LAN will meet the school's expanding networking requirements.

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I. The Research Problem

Introduction

In Lewis Carroll's famous seafaring tale, The Hunt for the Snark, the captain leading the expedition had wisely purchased a map to guide the courageous voyagers.

He had bought a large map representing the sea,
Without the least vestige of land:
And the crew were much pleased when they found it to be
A map they could all understand.

"What's the good of Mercator's North Poles and Equators,
Tropic, Zones, and Meridian Lines?"
So the Bellman would cry: and the crew would reply,
"They are merely conventional signs!

"Other maps are such shapes, with their islands and capes!
But we've got our brave Captain to thank"
(So the crew would protest) "that he's bought us the best---
A perfect and absolute blank!" (5:278)

The captain's blank map was merely a representation or model of the real world, although one certainly lacking any utility. When properly constructed these models help characterize and explain real world behavior and can be powerful aids in decision making. However, when poorly constructed they can be as useless as the captain's featureless map.

In recent years, researchers have applied various modeling approaches to the emerging field of local area networks (LANs). These networks are "data communications systems which allow a number of independent devices to communicate with one another" (18:1). They are usually located in a limited geographic area and provide one or more high speed communications channels with low error rates. The researchers were particularly interested in the performance evaluation of these LANs to help network designers implement effective and efficient network architectures. The ultimate purpose of the performance analysis models was to assist information systems personnel in implementing and maintaining cost effective networks which satisy user requirements. However, the researchers soon discovered that modeling LAN performance can be a complex and formidable task because of the large number of variables which can impact network performance. LAN topology, the physical transmission medium, network software and numbers and types of attached devices are just a few of these variables. These variables, like the map's "merely conventional signs" (5:278), must be fully understood to construct and effectively use LAN performance models.

General Issue

The Air Force's need for LAN performance evaluation models and for LANs in general results from the recent advances in information systems technology. In particular,

the growth in distributed computing has dramatically impacted the Air Force's approach to its mission and day-to-day operating activities. Desktop personal computers and workstations now complement the centralized data processing facilities on every base. Users, increasingly aware of the hardware and software resources available to them, demand ready access to information stored locally or at distant locations.

The proliferation of widely dispersed computer systems on Air Force bases require data transmission systems to connect them. The obvious solution originally pursued was to use the installed base telephone switch and telephone wire cable plant to provide data communications support. This approach worked well until the number of new terminal devices began outstripping available telephone wiring, and data transmission speed requirements began exceeding the limited capacity of the telephone circuitry (14:293-297). Information system managers, anxious to exploit the new decentralized computing power, began contracting for their own in-house data transmission systems, including fiber optic, coaxial cable, and other types of wiring to support these computer systems. These transmission systems, which are largely confined to one organization or site, became known as LANs. Appendix A contains a glossary of computer communication terms which will be used to characterize these networks.

The benefits offered by LANs are many: equipment integration, increased resource sharing, rapid system reconfiguration, and improved capacity and reliability (2: 75-78). A LAN is perceived as a means of improving productivity and efficiency by providing more facilities to network users in a convenient way. However, like other computing resources, these LANs must be carefully managed to insure optimal performance and operation. The performance of these networks is dependent upon the constraints imposed by the widely ranging technologies used to implement them. Topology, physical transmission media, and access control techniques are three primary user selectable determinants of LAN performance.

Performance characteristics must be considered not only in the planning and initial implementation of the LAN, but also as changes are made to the system. Information system managers must continually measure and reassess performance as new computing equipment is acquired and new requirements are levied on the system. Failure to do so will degrade network performance and eventually generate user dissatisfaction. Currently, many Air Force information systems personnel who manage LANs do not have a management tool for modeling the performance of their networks under widely ranging workloads and equipment configurations. In order to prevent LAN system degradation from impacting the Air Force mission, a method of objectively analyzing LAN performance under changing scenarios is required.

Specific Problem

The Air Force Institute of Technology (AFIT) is currently installing a LAN to provide complete physical and logical interconnection between computer resources located in seven separate buildings. The network will be extended to an eighth building, AFIT's new Science and Research facility, in 1988 when the construction on this building is completed. The computing environment to be supported consists of six mainframe computers and over 600 terminal devices and workstations. This network will employ a 75-ohm dual broadband coaxial cable architecture configured in a bus/tree topology. The transmission system uses community antenna television broadcast technology which enables all users to transmit and receive data from all other users on the network. Because it is a shared network, an access control mechanism must be used to regulate the flow of data on the transmission system. The network is designed to provide for growth of the computer systems and accommodate technical advances and on-going research efforts sponsored by the school.

AFIT will connect computer resources to the network with network interface devices. These devices have networking software which allows users to establish, conduct, and terminate user sessions across the network. AFIT selected the standard Department of Defense networking software, Transmission Control Protocol/Internet Protocol

(TCP/IP), for use in the network interface devices. To control access to the networks, the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol software will be used. CSMA/CD regulates user access to the shared network in a non-deterministic manner; any user with data can transmit as long as no one else is transmitting. In the event of a simultaneous transmission by two or more users, a collision occurs between the transmitted data and the CSMA/CD manages the recovery. The nature of CSMA/CD and the additional networking software used, combined with the LAN topology and transmission media, will determine the operating limits of the AFIT LAN. As new resources are added to the network, each with its own unique transmission characteristics, a re-evaluation of the capacity and performance of the network in this new environment must be made. Management must plan and prepare for surge requirements, new missions, and physical extensions of the network. Currently, AFIT has no simple, easy-to-use tool to adequately evaluate LAN performance under widely changing conditions.

Research Question

Can an LAN performance evaluation model be developed to allow AFIT information system managers to evaluate the impact of specific hardware and software changes on thei: local area network operation?

Research Objective

Develop a LAN performance model that will determine the impact of changing hardware and software configurations on the AFIT LAN.

Scope

This research is directed toward the development of a performance evaluation model for a broadband LAN employing the CSMA/CD access protocol. This model accounts for changing network lengths, varying network software implementations, and a variety of data traffic generating terminal devices. Although specifically developed for the AFIT LAN, the model and approach could be used to analyze other CSMA/CD broadband networks.

II. Literature Review

Introduction

The purpose of this literature review is to describe and summarize the research on performance evaluation models for local area networks with a particular emphasis on the CSMA/CD access method. As noted in Chapter 1, the nature of the access metnod will be a primary driver determining AFIT LAN performance. The goal is to establish a foundation for the modeling approach pursued in the methodology. The important findings of this research will be highlighted and several computer communications modeling strategies will be compared. Lastly, a performance model successfully used on a previous Air Force LAN acquisition will be identifed and offered as an approach for modeling the AFIT LAN.

This literature review uses the resources of the AFIT libraries and the Wright State University library. The majority of the sources were extracted from the _IEEE Transactions on Communications_ and _Computer Networks_, two professional journals dedicated to reporting communications issues.

Each of the sources under review addresses the problem of controlling access to a shared communications channel and suggests ways to measure the performance of the different access techniques. The basic problem is one of resolving conflicts when one user's packet, or package of data, is simultaneously placed on the shared channel with another

user's packet. The overlapping transmissions result in a collision which destroys both packets. One primary job of the access protocol, therefore, is to determine if the transmission was successful, and if not, to initiate retransmission of the data. The researchers identify a number of critical parameters which determine the performance of the access protocols on the networks. This review will explore these parameters and state how they impact performance. These parameters will drive the LAN performance model and are of the most concern to information system managers interested in the effective and efficient operation of their networks.

General Review of the Literature

Performance Studies of CSMA and CSMA/CD

Kleinrock and Tobagi present the first analysis of CSMA, a predecessor to CSMA/CD, in a 1975 research paper. They conclude that the CSMA contention protocol is "an efficient means for randomly accessing packet switched radio channels which have a small ratio of propagation delay to packet transmission time" (13:1413). This critical ratio, alpha, relates how long it takes energy to move through the transmission media to the time it takes to put a packet on the medium. Alpha is a function of the cable length, the channel bandwidth, and the packet length (18:32). Increases in the channel bandwidth or cable length, or decreases in

packet size, increase alpha and reduce efficiency. One other major finding was that as the channel traffic continues to increase, leading to more packet collisions, the channel exhibits unstable behavior and the performance rapidly decreases (13:1413].

Kleinrock and Tobagi also characterize the performance of CSMA using two standard measures of random access protocol performance: maximum achieved throughput, also known as channel capacity, and throughput-delay performance. Throughput is commonly stated as the average number of bits per second passing a certain point in the network (10:158). Throughput is often normalized by dividing it by the channel transmission rate to get a dimensionless quantity (10:158). Delay can be characterized in a number of ways. Most often, the average transfer delay is used. This delay includes the time a packet waits at the source network interface plus the time needed to transmit the packet across the LAN (10:156). Similar to throughput, the delay is often normalized by dividing by the average channel transmission time (10:159)

Later studies of contention protocols address channel performance in the presence of error-control traffic (24:815-826) and extend the performance analysis of CSMA to CSMA with collision detection (11:2023-2051; 15:763-774; 22:468-488). Collision detection is a feature of the CSMA/CD protocol which tells a source that its packet has been destroyed shortly after the collision occurs. CSMA/CD

is clearly shown to have improved throughput-delay characteristics over CSMA (23:257). Collision detection increases throughput and minimizes delays by reducing the time spent transmitting after a collision occurs. Once a collision is detected, the packet transmission is aborted and rescheduled for later transmission. The magnitude of the CSMA/CD performance improvement over CSMA is dependent upon the average retransmission delay and the collision recovery time (23:257). The value of alpha also plays a critical role in determining CSMA/CD performance. For small values of alpha, CSMA/CD is significantly better than CSMA; however, as alpha approaches 1, the difference in performance between the two protocols rapidly diminishes (10:336).

Tobagi and Hunt show that the traffic mix has an important impact on CSMA/CD throughput. When a mixture of short packets, which are characteristic of interactive users who require short transmission delays, and long packets, resulting from file transfers, are placed on the same channel, "the overall channel capacity is improved in favor of long packets and to the detriment of the throughput-delay performance of short packets" (23:257). This result suggests the need for priority schemes for interactive traffic (23:257).

Much of the pioneering development work on CSMA/CD based networks was performed by Xerox Corporation in the

early 1970's on its experimental network known as Ethernet. Two Xerox researchers, Shoch and Hupp, detail the actual measured performance of their CSMA/CD based Ethernet system in a 1980 research paper (20:711-721). The study shows that the system achieves throughput approaching 98 percent of channel capacity and demonstrates extremely stable behavior at artificially generated loads well over 100 percent (20:718). The system's ability to resist deadlock at high offered loads was a marked improvement over earlier random access protocols which degraded rapidly after reaching an optimal throughput capability. The composition of the traffic on their Ethernet network was divided between short packets containing terminal traffic and acknowledgements, and large packets containing file transfer data. This resulted in a bimodal distribution of packet lengths common to many LANs. Additionally, the nature of the applications tended to produce extremely bursty demands on the system. The peak demand was 37 percent of capacity while the average demand over the full day varied from only .60 to .84 percent (20:714).

In 1980, Xerox and two other corporations, Digital Equipment and Intel, developed a multicompany networking standard based upon the Ethernet design. Later that year, the Institute of Electrical and Electronic Engineers (IEEE) Computer Society formed a Local Networks Standards Committee, Project 802, to develop network standards for all

industry (9:184,194). The goal of the committee was to develop standards to promote compatibility between equipment made by different manufacturers to allow for simplified communications between their network devices (9:195). Because of the research community's considerable experience with the CSMA/CD based Ethernet, the IEEE 802 Committee pursued a standard based upon the Ethernet technique. The 802.3 subcommittee released a preliminary standard in December 1982 for a bus system that uses CSMA/CD as the access method. AFIT selected network hardware and software which complies with this standard.

Summary of CSMA and CSMA/CD Literature

In summary, CSMA/CD is shown to provide superior performance over CSMA. The critical design parameters which impact CSMA/CD performance are cable length, packet size, channel data rate, and the number and traffic distribution of terminal devices connected to the transmission system (18:274). Additionally, performance is influenced by the mixture of packet sizes. The addition of larger packets increases overall channel capacity and improves the throughput-delay performance of the larger packets at the expense of the smaller packets (23:257). The fundamental concern with CSMA/CD is that the maximum transfer delay cannot be bounded. This fact results from the random access nature of the protocol which can make the transmission channel unstable as the traffic load continues to increase

(18:274). The rising traffic load increases the collision rate which eventually drives the throughput to zero at very high loads. Kleinrock makes the dire prediction that as technology advances, leading to higher bandwith and longer cable length LANs, CSMA/CD will become progressively less efficient. The only solution would be longer packet lengths which are characteristic of file transfers, not interactive users (18:40).

Review of Computer Communication Modeling Approaches

There are two general approaches to modeling a computer communication system such as the AFIT LAN, analytic modeling and simulation (19:4). Analytic models incorporate mathematical equations which relate model parameters to performance measures. The solution to an analytic model is an exact result for the represented system (19:148). Analytic modeling, although often more abstract than simulation, generally makes smaller computational demands and is preferable when there is a direct relationship between the model parameters and the performance metrics (19:4-5). Analytic models are powerful intuitive tools which offer useful insignts through generally easy-to-understand formulas (25:1438). Poisson and Markov analysis are the two mathematical techniques most frequently used for the analytic performance analysis of random access protocols like CSMA/CD (21:13-22).

By contrast, simulation models can more closely represent the true system than analytic models. Simulation offers increased generality but often at increased cost for writing and executing the programs (19:5). And since each simulation run is essentially a statistical experiment, the results have statistical variability which must be carefully interpreted (19:148; 21:1424). Lastly, simulations can sometimes include so much detail about the original system as to make them unwieldy.

Computer communication systems are characterized by unpredictable sequences of random demands on the available resources. Fairly gross assumptions are made in both analytic and simulation models to approximate these systems and thereby keep the models tractable (25:1438). However, great care must be taken to ensure these approximations do not make the results of the model unrealistic, or worse, irrelevant. To validate the approach taken, analytic models are often applied to confirm simulations and vice versa (25:1438). Both modeling approaches comprise the primary tools available in the early network design stage. Only later, after the system is installed, can actual measurements of system usage and performance be taken. These measurements can in turn be used to modify and improve the existing models (25:1439).

Incremental Modeling

One technique commonly used for modeling local computer networks is incremental modeling. This approach involves constructing, simulating, and evaluating a model step-by-step until the entire system is effectively modeled (27:403). Figure 1 shows the steps involved in the functional modeling process and tools and methods necessary to accomplish them.

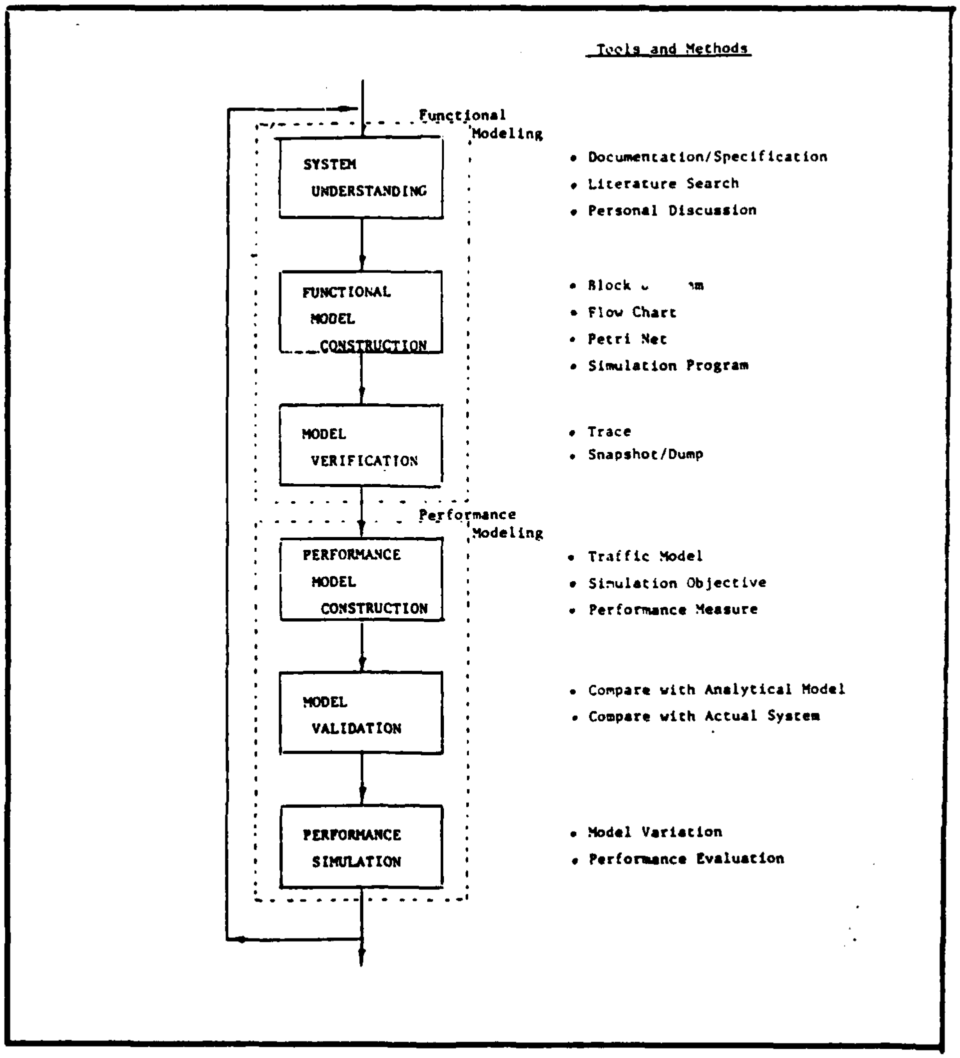

Fig. 1. Incremental Modeling Flowchart (27:408)

First, a functional model of the system is developed. To develop this model, documentation and detailed specifications of the system are collected and system experts are consulted. The goal of this step is to gain a good working understanding of the computer network and its many components. For a CSMA/CD network this step involves understanding the process where a sending source monitors the transmission medium. If the medium is idle, the source transmits; if busy, the source waits and attempts retransmission later (18:13). If a collision is detected during transmission, the transmission is immediately aborted and a short jamming signal is transmitted to let all the users know of the collision. After waiting a random amount of time, a retransmission is attempted.

The second part of the incremental modeling approach is performance modeling. This step evolves naturally from the functional model and its purpose is to gather statistics and measure the performance of the model (27:406). Here, performance measures such as collision rate, throughput, and utilization are defined for the simulation. Results from the simulation can then be used to validate the model. To develop the performance model of CSMA/CD, which operates between the interface device and the transmission medium, the traffic load going onto the network must first be characterized. The size, distribution, and propagation delay of the packets as they traverse the network from the

source to destination also must be defined. The impact of the random access nature of the CSMA/CD protocol and its dependence upon select design parameters can then be assessed. The incremental approach to modeling is an excellent approach for evaluating computer communication networks (27:416).

Summary of Modeling Literature

Two approaches to computer communications modeling, analytic modeling and simulation, are each shown to have specific advantages and disadvantages. Analytic modeling is appropriate when there is a direct relationship between the model parameters and measures of performance. Simulations offer greater generality but can be computationally tedious and costly. An incremental approach is shown to be one of the most useful techniques to perform this type of modeling.

Discussion of Previously Developed Model

Air Force Logistics Command is currently in the process of modernizing its logistics information systems. As part of this billion dollar effort, broadband local area networks are being installed at each of the command's five air logistics centers to provide communications support for the many new computer and terminal devices. These LANs are designed to support a baseline quantity of 5600 terminals and 1100 printers at each base. When completed these networks will be among the largest broadband LANs in the world.

In 1985, Mitre Corporation, the systems engineering firm designing these LANs, constructed an analytic model to predict the performance of these networks (7:56-86). This model was prepared in a spreadsheet format and was specifically tailored for the Logistics Command networks. Mitre pursued a conservative design approach, attempting to overestimate requirements to ensure that the communications system would not be undersized (6:13). Due to the extraordinary size of the Logistic Command networks, these networks were divided into multiple subnetworks at each base to achieve performance, reliability, and availability goals.

The general modeling approach taken was to first classify the type and quantity of digital data processing devices which would be connected to these LANs. These devices included asynchronous and synchronous terminals and printers, microcomputers, and host computers. Each device category was then characterized by its anticipated daily usage, or duty cycle, and device data rate per user session. CSMA was the access method selected and the standard Department of Defense networking software, TCP/IP, was specified as an example of a robust transport protocol. Packet sizes representative of this software were then stipulated for the model.

Two LAN performance measures were then selected for evaluation, throughput and delay. The analytic equations which approximate these measures were taken from the IEEE

literature for CSMA networks (22:471-475). To measure the throughput, the critical design parameter alpha was first calculated for a range of transmission distances corresponding to the electrical length in microseconds of each of the subnetworks. The maximum CSMA throughput was then determined over the range of alpha values. This throughput was de-rated by 50% to achieve a mean packet transmission delay of two packet times (7:64). This delay period was consistent with the Logistics Command's goal of a 99.9 % probability that a packet would be delivered across the LAN in less than one second. Mitre then estimated the minimum number of six megaherz channels required to support the projected device quantities at each site. A simulation tool was used to validate the modeling approach. The model successfully confirmed the technical approach being pursued on the Logistics Command networks (7:86).

There are many compelling aspects of the Mitre approach. The use of a standard spreadsheet package makes the model easy to develop and simple to run. The analytically derived expressions for throughput and delay which were based upon a Poisson analysis were simply entered in the model. Because it is an analytic approach, the implications of changing the design parameters are directly observable. By contrast, simulation models of similar networks can have hundreds of lines of code which can obscure variable relationships. Although both approaches

are needed, the analytic model is more suitable for managers interested in quickly evaluating network changes.

Summary

The primary research objective identified in Chapter One was to develop a LAN performance model to meet the needs of AFIT information systems managers. The literature in this field identified the critical LAN system parameters and offered several approaches to modeling these networks. Lastly, a successful modeling appoach pursued in a recent Air Force LAN acquisition was identified and evaluated. In the next chapter, the methodology for developing the model and confirming its validity are discussed.

III. Research Methodology

Introduction

The first chapter identified the need for a planning model to evaluate AFIT LAN performance under a variety of workloads and configurations. Chapter Two examined the literature in the field of CSMA/CD based networks and offered several approaches to model these networks. An existing LAN performance evaluation model was then reviewed and suggested as an approach to evaluate the performance of the AFIT LAN. This chapter explains the methodology to be used to develop a LAN performance model for AFIT use.

Model Selection

Because AFIT information systems managers do not currently have a technique to evaluate AFIT LAN performance, an analytic model will be created to portray this system. The research documented in Chapter Two indicates that an incremental model of the AFIT LAN is a valid technique to examine this performance. As noted earlier, the incremental modeling approach has two segments, functional modeling and performance modeling. The approach Mitre Corporation pursued on the AFLC networks offers a flexible and intuitively powerful means to accomplish the performance modeling segment of the incremental model.

The research uncovered no commercially available simulation models for IEEE Standard 802.3 CSMA/CD broadband

networks like the AFIT LAN. While both LAN researchers and vendors routinely develop simulation models for their specific CSMA/CD implementations, these models often include assumptions which would preclude direct comparisons to the AFIT network. Indeed, Shoch and Hupp, two of the original CSMA/CD network researchers, found other researchers investigating similar networks claiming simulation results directly contradicting their findings (20:720). The source of the disparity was a series of incorrect assumptions about the random access algorithm which dramatically altered the simulation results. Because no comparable simulation model was available, an analytic analysis will be pursued.

Assumptions

In general, analytic models are developed using the most tractable assumptions possible. Analytic models of CSMA/CD, and of other random access protocols like CSMA, often make two significant assumptions. The first is that the traffic source consists of an infinite population of users whose total number of packets generated has a Poisson distribution (23:248). These packet transmissions on the network have a mean arrival rate of lambda packets per second. This assumption approximates a network with a large but finite number of users in which each user generates packets infrequently. Each user in the infinite population is assumed to have only one packet requiring transmission at any time, including packets that previously collided and must now be retransmitted.

The second major assumption is that the average retransmission delay, the time a user delays the transmission of a previously collided packet, is arbitrarily large (23:248). This arbitrarily large retransmission delay is consistent with the assumption of Poisson traffic generation and ignores the specific retransmission algorithms. This assumption acts to reduce the apparent data throughput in the analytic model (10:389).

Procedure for Developing the Model

The incremental modeling approach discussed in Chapter Two will be followed to develop the analytic model. As with the original Mitre model, a conservative modeling approach will be pursued so as not to undersize AFIT requirements. Each of the two portions of this systematic modeling, functional modeling and performance modeling, will now be described in detail.

Functional Modeling

The first step in functional modeling is to understand the system. The CSMA/CD protocol used on the AFIT LAN complies with the IEEE Standard 802.3 for a broadband cable system that uses CSMA/CD as the access method. This published standard is based upon the Ethernet technique and packet sizes and provides an excellent technical source for understanding AFIT network operation. Additionally, vendor literature and technical experts were consulted about the

APIT LAN and they provided further insight into how the system will function. The Department of Defense Military Standards 1777 and 1778 provided the information on the TCP/IP networking software used in the network interface units.

The TCP/IP networking software was specifically developed for the Department of Defense to accomplish resource sharing across packet networks (4:8). To achieve this resource sharing, a layered hierarchy of interprocess communication oriented protocols were developed, each with a specific functionality (17:104). TCP provides a "connection-oriented data transfer that is reliable, ordered, full-duplex and flow controlled" (4:7) and is designed for environments where the loss, damage or misorder of packets can occur. IP resides below the TCP in the protocol hierarchy. It receives data from the TCP, packages the data in a self-contained packet known as an internet datagram, and passes the datagram to the lower level Ethernet layer. Here the datagram is encapsulated in another packet for transmission across the cable plant (3:1).

A simplified functional model of the system showing the interaction between the protocol layers in the network interface unit and the transmission medium was constructed. In this model the TCP protocol first receives the data from the transmitting device. While this data may contain headers from higher protocol layers, these protocols would

only be invoked under certain circumstances and they will not be accounted for in the model. The TCP then attaches a header to the data which contains addressing, acknowledgement, control and other information, and forwards this package to the IP software. IP adds its own header to the package including routing and identification information. IP also provides for fragmentation and reassembly of long packets. Indeed, the maximum internet datagram size is only 576 bytes (3:64). Large file transfers between devices, and files sent to printers would be divided into packets of this size. IP then passes the datagram to the Ethernet layer where the package is encapsulated with another header and an error control checksum. The contents and assigned lengths of the TCP and IP headers and Ethernet framing are given in Tables 1, 2 and 3.

TABLE 1. Transmission Control Protocol Header Fields

Name of Field	Size of Field
Source Port	16 bits
Destination Port	16 bits
Sequence Number	32 bits
Acknowledgement Number	32 bits
Data Offset	4 bits
Reserved Bits	6 bits
Control Bits	6 bits
Window	16 bits
Checksum	16 bits
Urgent Pointer	16 bits
Options	Variable

Total Length (w/o options)	160 bits

TABLE 2. Internet Protocol Header Fields

Name of Field	Size of Field
Version	4 bits
Internet Header Length	4 bits
Type of Service	8 bits
Total Length	16 bits
Identification	16 bits
Flags	3 bits
Fragment Offset	13 bits
Time to Live	8 bits
Protocol	8 bits
Header Checksum	16 bits
Source Address	32 bits
Destination Address	32 bits
Options	Variable

Total Length (w/o options)	160 bits

TABLE 3. IEEE 802/Ethernet Frame Format

Name of Field	Size of Field
Preamble	56 bits
Start Frame Delimiter	8 bits
Destination Address	16/48 bits
Source Address	16/48 bits
Length	16 bits
Logical Link Control Frame	24 bits
Logical Link Control Data	Variable
Pad	Variable
Frame Check Sequence	32 bits

Minimum Frame Length (w/o data)	168 bits

One important point about the TCP is that it employs a mechanism known as positive acknowledgement with retransmission to support reliable data transfer. This means that as connections, data transfers, and closings of connections occur on the network, the TCP software in both communicating interface units will confirm these actions by sending acknowledgement packets to one another (4:10). While these acknowledgements can sometimes be sent in the same packet as the data, a condition known as piggybacking, oftentimes these acknowledgements must be sent in separate packets. These acknowledgements act to increase th traffic load on the network.

To complete the functional model, a diagram of the CSMA/CD algorithm, Figure 2 provided a useful functional tool to understand the operation of the access protocol.

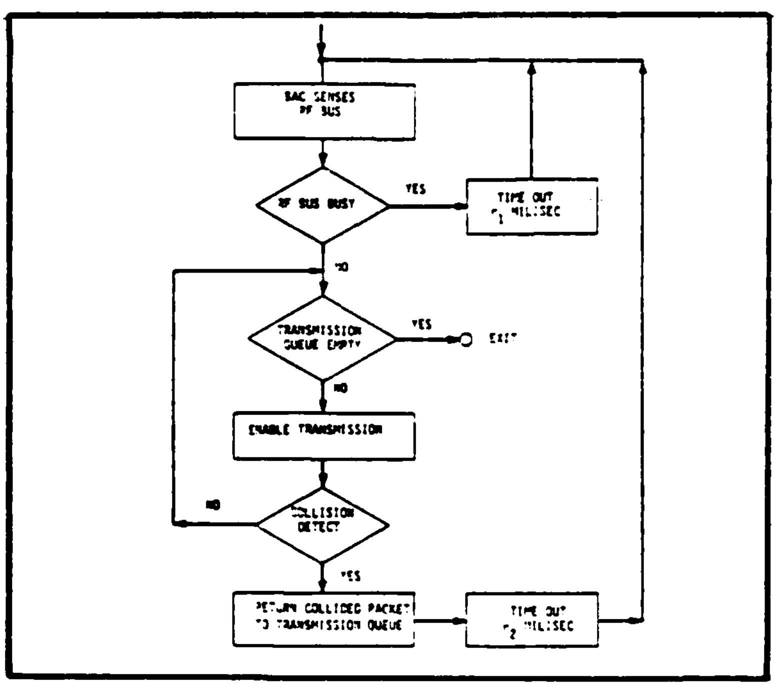

Fig. 2. Flow Chart for CSMA/CD Algorithm (16:87)

This flow chart was verified against the procedures outlined in the IEEE standard for CSMA/CD (12:34-38). This step completes the functional model.

Performance Modeling

The second, more difficult, segment in the modeling approach is the performance modeling. The first step in performance modeling is to characterize the traffic model which best represents the actual packet generation and processing by the network interface. Four different digital data processing devices which supply and receive data from the interace unit were considered: asynchronous terminals and printers, alphanumeric intelligent workstations, graphics intelligent workstations, and host computers. These devices will generate the bulk of the data traffic operating over the LAN, and each one of these devices has unique traffic generating characteristics which must be examined in detail (1:App II-IV).

Asynchronous Terminals and Printers. Asynchronous devices send and receive data without continuous character synchronization between the transmitting and receiving units. Virtually every terminal device which will operate over the AFIT LAN will be of this device type or can emulate an asynchronous terminal. Indeed, AFIT has 469 devices which can operate in the asynchronous terminal mode (1:App III). Included in the classification are Heath and Visual keyboard/display terminals.

Asynchronous terminals typically operate in either an echoplex or block mode. In echoplex mode every character entered at the terminal must be "echoed" by the host computer before it is displayed at the terminal screen. Therefore, each character as it is entered generates a packet in the interface unit which is sent to the host computer. Correspondingly, the host responds by sending the same character to its interface unit which generates a packet back to the terminal where the character then appears on the terminal screen. In addition, for every packet of data sent, an acknowledgement packet is sent from the receiving network interface to the sending interface to inform that the packet was received correctly. Therefore, in a worst case situation, when there is no piggybacking of acknowledgement and echoed packets, for every character entered in ecnoplex mode four packets are generated on the network. Because of the large number of packets generated from each character transmission, and because these packets are generally the minimum length allowable, echoplex traffic typically places the greatest burden on the communications channel. AFIT information systems personnel estimate that fully 85 percent of the packets sent over the LAN will be single character packets (1:17).

While operating in the more efficient block mode, asynschronous terminals typically buffer a complete 80-character line of data before transmitting to the host

computer. Therefore block mode traffic generates larger packet sizes with correspondingly less overhead required. However, virtually none of the AFIT devices operate in block mode.

Lastly, AFIT has a large number of asynchronous printers which will be placed on a separate channel on the LAN. Printer traffic is one-way traffic from the host or intelligent workstation to the printers. The packet sizes generated to the printers are generally quite large with proportionally less overhead than echoplex traffic. Since the maximum IP datagram size is 576 bytes the printer traffic will be segmented into packets of this size.

Alphanumeric Intelligent Workstations. AFIT has a large investment in intelligent workstations such as the Convergent Technologies B-25 systems and deliveries of Zenith Z-248 microcomputers continue. When in terminal emulation mode these devices generate traffic identical to asynchronous terminals. However, when transferring their own data these devices act as small host computers transmitting files. The size of these file transfers is restricted by the limited on-line storage capacity of the workstations. However, data transfer rates ranging from 4 thousand to two million bits per second are considered normal (2:84). AFIT information systems personnel estimate that 15 percent of the packets sent over the network will be file transfer packets of 576 bytes per packet (1:17).

Graphics Intelligent Workstation. AFIT currently has few of these devices but with the expansion of AFIT facilities anticipated with the completion of the new Science and Research facility in 1988, increasing numbers of graphics workstation devices can be expected. If the graphics are generated internally from small amounts of host data, normal terminal data rates of about twenty thousand bits per second are usually sufficient. These devices could be attached to the same LAN channels as the interactive traffic. However, if the workstation displays images generated from a centralized host, data rates from fifty thousand to twenty-five million bits per second are typically generated (2:84). Special high-speed interfaces to the network are then required and it is necessary to segregate this traffic on a LAN channel separate from the interactive traffic to maintain timely responses over the network. For this analysis the graphics are assumed to be internally generated so the transmissions over the LAN will be single character packets.

Host Computers. AFIT's four VAX 11/785s and a Harris 800 are the primary computing systems at the school and provide the many scientific and managerial applications which need to be accessed. These computers will support most of the terminal and printer devices on the AFIT LAN. Host computer traffic requirements can be derived from the various devices which access them. For example, the

asynchronous terminals operating in echoplex mode can anticipate a full screen of data from the host for every 80 characters entered.

Traffic Analysis

For this analysis, each device type was assumed to generate its own standard packet size with a fixed amount of overhead associated with each packet. The IEEE Standard 802.3 Ethernet frame format was assumed for all packets and protocol overhead consistent with the Ethernet framing and TCP/IP protocols was applied. The Ethernet standard stipulates a minimum packet size of 64 bytes with the data field ranging from 46 to 1500 bytes (10:385). However, a maximum data field size of 576 bytes, which includes the TCP and IP headers, was used since this number corresponds to the maximum IP packet size allowable within the Ethernet frame (3:64). Characteristic of many LANs, the AFIT LAN will exhibit a bimodal packet length distribution. The asynchronous and graphics devices will generate minimum size packets, while the devices sending file transfers and printer files will generate the maximum size packets allowable by the standard. Acknowledgement packets will also be of minimum size. The structure for these packets is listed in Table 4.

Table 4. Application Packet Structure (bytes)

Application	Data	TCP	IP	Padding	Ethernet Frame	Total
Echoplex Data Entry	1	20	20	2	21	64
File Transfer	536	20	20	0	21	597
Acknowledgment Packet	-	20	20	3	21	64

Each device was assumed to have constant operation or duty cycles and constant transmission rates. The transmission rates are approximations based upon the applications that will normally be performed by the devices. For example, each asynchronous terminal is assumed to generate 80 echoplex characters, equal to one line of data, followed by a full screen response of 1920 characters from the host computer. This transaction approximates a normal database request. The sequence repeats every 2 minutes. Each echoplex character generates four 64-byte packets, 2 data and 2 acknowledgement packets, for a total of 1365 bits per second for the 80 characters. The host responds with approximately four 597-byte packets which would be acknowledged by four 64-byte acknowledgements. The aggregate rate generated by the host will be 161 bits per second with a composite total between host and terminal device of 1526 bits per second. A similar analysis was

carried out for the other devices and the results portrayed in Table 5.

Table 5. CSMA/CD Traffic Model Aggregate Data Rates

Device	Transmits	Receives	Repeats Every	Duty Cycle	Data Rate (bps)
Echoplex Asynchronous Terminal	80 char	1920 char	2 min	75%	1526
Alphanumeric Workstation File Transfer	80 char	19200 char	2 min	15%	2945
Graphics Workstation	80 char	1920 char	4 min	75%	764
Printer	-	16000 char	2 min	50%	1317

Note: Single character echoplex traffic will make up 85% of the total traffic on the AFIT LAN. The balance will consist of file transfers between workstations and print files sent from hosts to printers.

Performance Evaluation

Three performance measures were selected to evaluate network performance. These measures include maximum channel efficiency, throughput, and minimum average transfer delay. These measures are included in the model output shown in Appendix B.

Channel Efficiency. The channel efficiency or channel capacity is the maximum achievable throughput for that access mode. In an ideal environment, packets would be perfectly scheduled so that there would be no collisions or

gaps between packets. The throughput would then be equal to 1. In practice though, there will always be interference problems and idle time which reduce the throughput below 1. It is useful for network managers to understand the parameters which impact the channel efficiency of a CSMA/CD LAN and correspondingly permit effective sharing of the medium.

The maximum channel efficiency of a CSMA/CD LAN is approximated by Kleinrock to be (18:32):

$$\text{C.E.} = 100/(1 + 5.145\,a) \qquad \text{for} \quad a <= 0.5 \qquad (1)$$

$$= 14/a \qquad \text{for} \quad a >= 0.5 \qquad (2)$$

where

C.E. = Channel Efficiency (percentage)

Alpha (a) = Ratio of Propagation Delay to Packet Transmission Time

$$\text{Alpha } (a) = 5LC/b \qquad (3)$$

where

L = Cable length (kilometers)

C = Channel bandwidth (megabits/sec)

b = Packet length (bits/packet)

Further, Kleinrock assumes that the signal takes 5 microseconds to travel one kilometer in the coaxial cable, the packet lengths are fixed, and users are separated by the full length of cable (18:31-32). For the AFIT LAN channel

efficiency analysis the conservative assumption of 64 bytes (512 bits) per packet was made.

Throughput Analysis. Throughput equations exist for the CSMA/CD protocol and its many refinements (10:325-333). One expression for the normalized throughput of the non-persistent version of CSMA/CD is (16:87):

$$S = \frac{Ge^{(-aG)}}{(1+a)Ge^{(aG)} + (1+aG)((1-e^{(-aG)})^{2} + 1} \qquad (4)$$

where

S = Normalized throughput

G = Normalized offered packet traffic

a = Alpha

e = Base of the natural logarithm (equal to 2.81828)

However, this expression is a transcendental equation which must be solved for G by trial and error. Tables are available which offer ranges of G for fixed values of S and Alpha (16:87). Since network managers seldom, if ever, examine or understand such parameters as normalized offered traffic, an alternative analysis was pursued. Using equation 1 and the individual packet and traffic models developed earlier, the maximum throughput for each device category was calculated over a LAN cable length distance from .2 to 5 kilometers. The maximum number of devices which could be supported at that throughput level was then calculated by dividing by the average number of bits per

second for that device's transmission cycle. By adding the fraction of channels required to support these devices individually, the number of six megaherz channels needed to support all of the AFIT equipment was determined. This information is given in Appendix B.

Delay Analysis. Analytic studies of delay for CSMA/CD networks are difficult to approximate and have only been carried out for one specific case (10:335). To offer the network manager some insight into the delay on the network an evaluation of the minimum average delay was made. The minimum average transfer delay is given by (10:400):

$$T = X/R + EED/3 \qquad (5)$$

wnere

T = Minimum average transfer delay (microseconds)

X = Average length of a packet (bits)

R = Channel bit rate (bits per second)

EED = End-to-end propagation delay (microseconds)

$X = (.85 \times 512) + (.15 \times 5256) = 1224$ bits

Because the AFIT LAN uses a device known as a remodulating head-end and plans to bridge to and from its host computers connected to one another on baseband cable, additional delays will be incurred at these points. The bridge delay each way is 40 microseconds and the head-end remodulation time is 5 microseconds. This additional 85 microsecond delay was added to the minimum average delay in the model.

Model Validation

The fifth step in incremental modeling is model validation. Of particular interest was validation of the equation for channel efficiency which was used for both the throughput and capacity analysis. A currently operational CSMA/CD LAN system located at HQ AFLC was selected to verify the external validity of the model. This network uses the same access method and similar packets sizes and traffic distribution as the AFIT LAN. The test performed was a simulation to measure the channel efficiency on the HQ AFLC Network. This maximum throughput was measured for a fixed alpha and was run over the full range of traffic load, 0-100%. A device known as a traffic generator was used to artificially generate packets onto the HQ AFLC network. This device simulates normal traffic patterns by sending packets between 64 and 1514 bytes long onto the LAN (26:TG-3). It is designed to simulate a network containing mostly asynchronous terminal traffic, very similar to the traffic which will operate over the AFIT LAN. The traffic generator imposes a constant load ranging from 0-100% on the LAN.

While the traffic generator is loading the network a companion device known as a cable monitor passively observes the network load. It records network traffic during specific reporting periods which the user determines. The network load is measured as period of time that a voltage signal representing data is present on the channel. The

resulting data from the cable monitor were then compared to the analytic results from the model. The results given in Appendix C give credence to the modeling approach.

A second test was conducted to verify the approximation for minimum average transfer delay. Using an Hewlett-Packard 4953A protocol analyzer, a simple program was written to measure the delay in sending a character to and from a network interface unit across the network. All of the values recorded were in excess of the predicted minimum delay. However, it proved difficult to reliably factor out the delay due to the processing time incurred in the network interface from the total transmission time. Additionally, the sensitivity of the protocol analyzer was only .1 milliseconds, a significant amount of the average transfer delay expected. Therefore, these results were inconclusive.

Sensitivity Analysis

The sensitivity of the throughput model to the three critical variables: propagation delay, channel data rate and protocol overhead was examined. In each case one of these variables was changed while keeping the others constant. The results of the analysis are shown as a function of channel requirements. The current AFIT basic configuration of 469 echoplex terminals and 100 asynchronous printers with a 2 kilometer maximum cable length was used. A two megabit channel data rate with 40 bytes of TCP/IP overhead and 21 bytes of Ethernet framing was considered. In the basic

design two six megaherz channels were needed to satisfy the data requirements.

Propagation Delay. Since future extensions of the AFIT LAN to the new Science and Research facility are anticipated, changes in propagation delay are particularly important. The effect of increasing propagation delay was analyzed between .2 and 5 kilometers. The cable length was increased by .2 kilometer increments while the base channel rate and protocol overhead were held constant. At the upper end no additional channels are needed to accommodate the traffic.

Channel Data Rate. The operating channel rate of the network interface units was varied over the specific range of commercially available products, 128 kilobits per second to ten megabits per second. At the lower end 5 additional channels are needed. At the high end, the minimum number of channels is still required.

Protocol Overhead. Network researchers continue to debate the need for TCP/IP software operating on a LAN (17:133-143). The extremely good error properties of the cable and the cyclic redundancy check present in the Ethernet frame seem to eliminate the need for the error control properties of the TCP/IP. However, in AFIT's case the addition of the TCP/IP presents no real additional overhead burden because the bulk of the packets are single character and would require 42 bytes of wasted padding

without the 40 bytes of TCP/IP. The only real impact would be a small TCP/IP processing time delay in the interface unit. The Department of Defense has strongly encouraged the use of TCP/IP on LANs where equipment interchangeability and network survivability are perceived needs (3:1).

The impact of protocol overhead varying from 61 to 141 bytes was examined. This additional overhead could result from implementing several of the options under TCP and IP such as security, record routing, and maximum segment size (3:38; 4:93). The addition of more overhead required no additional channels.

Summary

This chapter contained the modeling approach used to develop the performance evaluation model for AFIT use. A network simulation on a currently operational LAN provided some confirmation that the modeling approach taken was valid. The next chapter discusses the conclusions based on the research findings and offers recommendations for future work in this area.

IV. Conclusions and Recommendations

Research Summary

This research effort proposes an analytic model which evaluates the impact of changing hardware and software configurations on the CSMA/CD based AFIT LAN. The model examines individual traffic models for the different networked devices and uses analytic approximations for efficiency, throughput and delay to calculate the performance measures. A network loading test performed on a similar network at HQ AFLC provides confirmation for the modeling approach.

The model offers the AFIT LAN network managers two significant capabilities. Because the model is constructed in a spreadsheet, it is simple to use and places minimal computational demands on the computing system. Second, critical parameters such as cable length, packet sizes and channel data rate can be easily modified in one location to examine their impact on network operation. These "what if" type evaluations offer decision makers a powerful network management tool.

Practical Implications of the Model

The results of the modeling analysis when the planned AFIT LAN configuration parameters are entered illustrate the considerable flexibility and capacity of the network. The AFIT LAN channel efficiency analysis indicates that each

network channel can achieve a maximum throughput of 83.25% of the channel data rate. In worst case situation, where all the devices are generating single character echoplex packets, fully 1455 devices can be supported on one channel. The benefits of larger packet sizes are seen by comparing the aggregate througnput for file transfer applications to echoplex transactions. When file transfer packets are sent exclusively, the maximum throughput is 1958 kilobits per second versus 1665 kilobits per second for only echoplex transactions. The minimum average transfer delay over the AFIT LAN will approximate 700 microseconds.

The sensitivity analysis results indicate AFIT will have no problem extending the network to the new Science and Research facility. The additional network length, about .2 kilometers, will only have a marginal impact on network performance. Additionally, as long as AFIT continues to use network interface units operating at speeds in excess of 1 megabit per second only 2 data channels are required, one for terminals and one for printers. Lastly, if AFIT opts to employ additional options available with TCP/IP such as security, tnis too will only have a marginal impact on performance and require no additional channels.

With over 60 channels potentially available on the AFIT LAN it is obvious that the network will satisfy AFIT's data transmission requirements. However, many of these channels will be dedicated to other user applications such as video,

high speed host-to-host transfers and point-to-point connections. Also, it is important to note that vendors recommend that any single data channel should not be loaded over 30%. Because CSMA/CD is a contention protocol its performance at high offered loads becomes unstable. The subsequent result of high loading is longer delays in the network interface unit with decreasing end-to-end response time to the user. Network monitors such as those used in the validation test will inform managers when channel usage reaches an undesirable level. Users should then be moved to new channels to alleviate the load.

Recommended Improvements

The model was prepared without the benefit of measurements from the actual AFIT LAN system. The individual traffic models are just approximations based upon current system usage. Once the system is completed measurements of actual network usage and behavior should be gathered to validate and improve upon the analytic model. The evaluation of changing network hardware and software implementations can then be more reliably assessed.

Also, more work needs to be done in the area of network delay. User response time is a critical factor which affects user acceptance of a computing system. If the user encounters significant delays on the network due to lengthy transmission times or processing delays at the interface unit, they will be less inclined to use the system. For

network managers then, it is important to understand where the delays can occur and how to minimize them. More work needs to be done in estimating this delay.

Further Research

AFIT informations sytems personnel plan to connect the AFIT LAN to other commercial and Department of Defense networks (1:App VII). Networks such as the Defense Data Network and BitNet are wide area networks which typically operate at speeds of 20 to 64 thousand bits per second. There are potential problems with congestion control at the gateways between the AFIT LAN and these networks as data running in the megabits per second range is passed to much slower networks. In particular, the Internet Control Message Protocol, a part of the Internet Protocol which operates at the gateways and reports IP processing errors, may experience congestion problems (8:48). Since this problem may impact Defense Department networks worldwide, it suggests a fruitful area of research.

In the future the AFIT LAN will be used to support high speed host-to-host file transfers, high speed graphics, video, and a wide range of other applications. With the addition of these services, the true promise of this network will be fully realized. There are many potential research projects which could analyze network performance and network management requirements when all these services are implemented. Additionally, new access methods and new

technologies in the field could be evaluated for potential AFIT and Air Force use. To encourage future research in this area, AFIT should set aside several LAN channels for student use in research projects. This would only take away a fraction of the available capacity and open up a wide range of networking projects.

Appendix A: Glossary of Computer Communication Terms

a. Acknowledgement. A transmission control code which is returned by a receiving terminal to a transmitting terminal to acknowledge that a frame of information has been correctly received.

b. Asynchronous Transmission. Transmission in which each information character or sometimes each word or small block is individually synchronized, usually by the use of start and stop elements. The gap between each character or word is not of necessarily fixed length.

c. Bit. The smallest unit of storage in a binary computer. Bit stands for binary digit and can have the value of 0 or 1.

d. Broadband LAN. A local area network in which information is transmitted on modulated carriers, allowing coexistence of multiple simultaneous services on a single physical medium by frequency division multiplexing.

e. Byte. A single character of information storage, such as a letter, number or punctuation mark. A byte contains 8 bits.

f. CATV-type Broadband Medium. A broadband system comprising coaxial cables, taps, splitters, amplifiers, and connectors the same as those used in Community Antenna Television (CATV) or cable television installations.

g. Channel. A band of frequencies dedicated to a certain service transmitted on the broadband medium.

h. Coaxial Cable. A two conductor, concentric (center conductor and shield), constant impedence transmission line.

i. Collision. Event in which two nodes transmit simultaneously, rendering both messages unintelligible.

j. CSMA/CD. Carrier Sense Multiple Access/Collision Detection is a network protocol in which every node transmits messages as soon as it needs to and finds the network is quiet. A collision occurs if two nodes transmit at the same time. Collisions are

detected and the transmission is resent after a delay of variable length.

k. Datagram. A self-contained package of data carrying enough information to be routed from source to destination without reliance on earlier exchanges between source and destination and the transporting network.

l. Dual-Cable. A broadband coaxial cable system in which separate coaxial cables are used for the forward and reverse direction of signal transmission. Connection of a dual-cable system to a station require dual F-connectors at the station - one for transmission and one for reception.

m. Echoplex. A error-detection method where characters sent by a terminal are sent back to the terminal and displayed. Recovery from the error is a human-driven procedure.

n. Ethernet. A baseband local area network developed by Digital Equipment Corporation, Intel Corporation, and Xerox Corporation. Ethernet uses the CSMA/CD protocol and has a bandwidth of 10 megabits per second.

o. Host. A computer system on which applications can be executed and which also provides a service to users of a computer network.

p. IEEE 802. The Institute for Electrical and Electronic Engineers standard committee number 802 is responsible for developing network standards. The 802.3 subcommittee works on a standard derived from Ethernet.

q. IP. An internetworking protocol that provides connectionless service across multiple packet-switched networks.

r. Local Area Network. A system that connects computers together within a restricted geographic area, usually a mile or so, to allow sharing of information and hardware resources; also called a LAN.

s. Overhead Bits. Signal elements which are added to information bits as part of the management of a communications process, and not intended for transmission to the end user.

t. Packet. A block of data with a defined format containing control and data fields.

u. Packet Switching. A term used in a data transmission network which is designed to carry the data in the form of packets. The data, in packets, is passed to the network, and devices within it use the control information to transmit the packet to the correct destination.

v. Protocol. A formal set of conventions governing the format and relative timing of message exchange between two communicating processes.

w. Session. When two pieces of software, two users, resources, or other components in a network, are connected together for the purpose of exchanging information, they are said to be in session.

x. TCP. A transport protocol providing connection-oriented, end-to-end reliable data transmission in packet switched computer subnetworks and internetworks.

APPENDIX B: Sample Model Output

```
AGGREGATE DATA RATE CALCULATION
======================================================

ECHOPLEX TRANSACTION DEVICE

DEVICE CONTRIBUTION
PACKETS/CYCLE =          80 ROUNDING =              80
DATA RATE =        1365.333 ROUNDING =            1365

HOST CONTRIBUTION
PACKETS/CYCLE =    3.582089 ROUNDING =               4
DATA RATE =        161.3333 ROUNDING =             161

AGGREGATE RATE =       1526 BITS/SEC
======================================================
FILE TRANSFER

DEVICE CONTRIBUTION
PACKETS/CYCLE =          80 ROUNDING =              80
DATA RATE =        1365.333 ROUNDING =            1365

HOST CONTRIBUTION
PACKETS/CYCLE =    35.82089 ROUNDING =              36
DATA RATE =            1580 ROUNDING =            1580

AGGREGATE RATE =       2945 BITS/SEC
======================================================
GRAPHICS DEVICE TRANSACTION

DEVICE CONTRIBUTION
PACKETS/CYCLE =          80 ROUNDING =              80
DATA RATE =        682.6666 ROUNDING =             683

HOST CONTRIBUTION
PACKETS/CYCLE =    3.582089 ROUNDING =               4
DATA RATE =        80.66666 ROUNDING =              81

AGGREGATE RATE =        764 BITS/SEC
======================================================
 PRINTER

RECEIVES FROM HOST
PACKETS/CYCLE =    29.85074 ROUNDING =              30
DATA RATE =        1316.666 ROUNDING =            1317

AGGREGATE RATE =       1317 BITS/SEC
```

AFIT LAN CHANNEL CAPACITY ANALYSIS

Trunk Data Rate =	2	Megabits/Sec		
Minimum Packet Overhead =	61	Bytes		
Cable Length =	0.2	to	5	Kilometers

Fixed Packet Size Analysis:

Echoplex Transaction Packet Size:	64	Bytes
File Transfer Packet Size:	597	Bytes
Graphics Data Packet Size:	597	Bytes
Printer Packet Size:	597	Bytes
Acknowledgment Packet Size:	64	Bytes

SESSION DATA RATE REQUIREMENTS:

	Avg bps	No. Devices	Fraction Traffic
Echoplex Transaction =	1526	449	0.85
File Transfer =	2945	40	0.15
Graphics Data Transfer =	764	10	0
Printer =	1317	100	1

Design = 2817.75 Rounding = 2818

TYPE	TRANSMISSION/CYCLE BYTES DEVICE	HOST	SECONDS/ CYCLE	BYTES OVERHEAD	TRANSMISSION BYTES OF DATA DEVICE PACKET	HOST PACKET
ET	80	1920	120	63	1	536
FT	80	19200	120	61	1	536
GDT	80	1920	240	63	1	536
PRINTER		16000	120	61		536

CHANNEL CAPACITY ANALYSIS
Packet Length = 512 Bits

Cable Len Kilometer	Alpha	CAPACITY %
0.2	0.0039	98.03
0.4	0.0078	96.14
0.6	0.0117	94.32
0.8	0.0156	92.57
1	0.0195	90.88
1.2	0.0234	89.25
1.4	0.0273	87.68
1.6	0.0312	86.17
1.8	0.0352	84.67
2	0.0391	83.25
2.2	0.043	81.88
2.4	0.0469	80.56
2.6	0.0508	79.28
2.8	0.0547	78.04
3	0.0586	76.83
3.2	0.0625	75.67
3.4	0.0664	74.54
3.6	0.0703	73.44
3.8	0.0742	72.37
4	0.0781	71.34
4.2	0.082	70.33
4.4	0.0859	69.35
4.6	0.0898	68.4
4.8	0.0938	67.45
5	0.0977	66.55

Echoplex Asynch Terminal		Graphics Terminal	
Thruput Kbps	No. of Devices	Thruput Kbps	No. of Devices
1961	1713	1961	3422
1923	1680	1923	3356
1886	1648	1886	3291
1851	1617	1851	3230
1818	1588	1818	3173
1785	1560	1785	3115
1754	1533	1754	3061
1723	1505	1723	3007
1693	1479	1693	2955
1665	1455	1665	2906
1638	1431	1638	2859
1611	1408	1611	2812
1586	1386	1586	2768
1561	1364	1561	2724
1537	1343	1537	2682
1513	1322	1513	2640
1491	1303	1491	2602
1469	1284	1469	2564
1447	1264	1447	2525
1427	1247	1427	2490
1407	1229	1407	2455
1387	1212	1387	2421
1368	1195	1368	2387
1349	1179	1349	2354
1331	1163	1331	2323

File Transfer		Printer	
Thruput Kbps	No. of Devices	Thruput Kbps	No. of Devices
1996	4518	1996	3031
1991	4507	1991	3024
1987	4498	1987	3017
1983	4489	1983	3011
1979	4480	1979	3005
1975	4471	1975	2999
1970	4460	1970	2992
1966	4450	1966	2986
1962	4441	1962	2979
1958	4432	1958	2973
1954	4423	1954	2967
1950	4414	1950	2961
1946	4405	1946	2955
1941	4394	1941	2948
1937	4385	1937	2942
1933	4376	1933	2935
1929	4367	1929	2929
1925	4358	1925	2923
1921	4349	1921	2917
1917	4340	1917	2911
1913	4331	1913	2905
1910	4324	1910	2901
1906	4315	1906	2894
1902	4306	1902	2888
1898	4297	1898	2882

AVERAGE PACKET LENGTH = 1224 bits
CHANNEL BIT RATE = 2 Mbps
AVERAGE BRIDGE DELAY = 40 microsec
HEADEND REMODULATION TIME = 5 microsec

DELAY ANALYSIS

Microsecs
697
698
698
698
699
699
699
700
700
700
701
701
701
702
702
702
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704
704
704
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705
705

Appendix C: Results of Model Verification

The HQ AFLC local area network is a dual broadband cable system which uses CSMA/CD as the access method. It uses network interface units which operate at 5 megabits per second with packet lengths and traffic distribution very similar to the AFIT LAN. Using a maximum round trip cable length of .41 kilometers and standard packet size of 64 bytes, the model predicts a channel efficiency of 90.66%. If the model is a good predictor of this measure of maximum throughput, the network load should peak at this point. The sampling procedure for the test and results are discussed below.

While the traffic generator increases the load on the network the cable monitor samples the channel once every 256 microseconds producing 10,000 samples every 2.56 milliseconds. The monitor averages these samples every 5 seconds and reports the high, low and average readings at one minute intervals. The results are given in percentages of load. The load present before the traffic generator was turned on represents traffic generated by some of the 750 terminal devices connected to this channel. The results of the channel efficiency test are given in Table 5.

Table 6. Channel Efficiency Test (%)

Imposed Load	High	Low	Average
0	3.18	1.45	2.44
10	13.18	11.62	12.47
20	22.59	21.17	21.74
30	33.43	30.94	32.10
40	42.36	41.27	41.74
50	52.99	51.33	52.08
60	63.78	62.23	63.08
70	78.47	76.03	76.86
80	89.27	86.33	87.90
85	91.58	90.91	91.30
90	91.71	91.17	91.49
92	91.78	91.28	91.47
94	91.58	91.30	91.45
100	91.76	90.92	91.46

The test demonstrated a maximum average channel efficiency rate approaching 91.5%. This is about 1% more than the model predicts. One possible explanation for the disparity is that the traffic generator is designed to send out 64 byte packets when generating small loads, but increases packet sizes to as much as 1514 bytes at higher imposed loads. As shown by the Tobagi and Hunt study, the addition of larger packets allows the channel to recover a fraction of its excess capacity (23:256). The test was based on packet sizes of 64 bytes, 512 bits, as a

conservative assumption. The test appears to validate the approach taken to analyze the channel requirements for the AFIT LAN.

One unfortunate and unexpected consequence of the test was the failure of 12 network interface units on the channel. The vendor of these units suggests that the failure was due to buffer overflow resulting from the increasing traffic load which corrupted memory locations. The units were manually reset and returned to service.

Collision Analysis

In conjunction with the channel efficiency test another test was conducted to observe the number of collisions as the traffic load increased. A terminal was connected to a host computer over the network and a large text file (40 pages) was scrolled to the screen. Concurrently, fault detection software which gave status information on the terminal's network interface unit was run as the network load was increased. The fault detector gave information on the following 5 characteristics: number of transmitted packets (TR), number of received packets (R), number of collisions (Col), number of cyclic redundancy check errors (CRC), and number of lost packets (NLP). Five 5-second samples were observed at each 10% increase of traffic load. The results are recorded in Table 6.

Table 7. Fault Detection Observations

Imposed Load	TR	R	Col	CRC	NLP
0	39	125	0	0	0
	36	108	0	0	0
	36	105	0	0	0
	40	126	0	0	0
	35	106	0	0	0
10	36	104	0	0	0
	36	106	2	1	0
	35	98	2	1	0
	37	108	0	0	0
	36	106	1	0	0
20	45	125	2	0	0
	55	146	4	1	0
	51	146	6	1	0
	49	147	4	0	0
	50	147	4	0	0
30	54	139	1	1	0
	40	138	5	2	0
	47	123	2	0	0
	60	133	7	1	0
	43	122	4	2	0
40	54	185	1	0	0
	55	161	12	0	0
	53	147	6	1	0
	54	135	1	0	0
	43	128	5	1	0
50	39	102	6	1	0
	47	118	4	0	0
	46	129	11	2	0
	44	112	4	0	0
	44	124	6	1	0
60	65	165	12	2	0
	34	89	10	0	0
	52	131	16	0	0
	45	113	15	8	0
	56	122	24	0	0
70	64	147	35	5	0
	61	141	39	1	0
	44	119	39	1	0
	49	120	33	3	0
	48	132	38	6	0

Table 7. Fault Detection Observations (Con't)

Imposed Load	TR	R	Col	CRC	NLP
80	44	104	33	2	0
	34	88	32	5	0
	40	97	29	6	0
	45	98	24	7	0
	56	123	24	1	0
90	62	123	40	2	0
	43	110	32	7	0
	60	121	64	5	0
	50	123	40	2	0
	49	129	40	5	0
100	49	115	40	3	0
	36	94	24	1	0
	50	130	42	8	0
	52	102	36	8	0
	51	128	54	7	0

It is apparent and expected that as the traffic load increases the collision rate also increases. At maximum loading there are almost as many collisions as packets transmitted for that interface unit. However, even at these extreme loads the network continues to function, although more slowly as collisions and the resultant retransmissions consume more of the channel capacity. The cyclic redundancy check errors on the received packets also increased with network load. This increase indicates transmission problems resulting from the high traffic load.

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Block 19. Abstract

The purpose of this study was to develop a performance evaluation model to analyze the impact of changing hardware and software configurations on a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) based local area network (LAN). The analysis focuses on the specific network software and computing equipment used on the Air Force Institute of Technology (AFIT) LAN.

The analysis was accomplished in two parts. First, a functional model of the network was prepared using available technical documentation and by consulting with system experts. The second part of the process was performance modeling. Individual traffic loading models were developed for each device to be connected to the AFIT LAN. Packet sizes characteristic of the networking software and access method were then specified for each device, and an aggregate data rate for each device was computed. Three performance measures: maximum channel efficiency, throughput, and minimum average delay were then selected to evaluate overall network performance. A standard spreadsheet program was used to construct the model. The results of the modeling analysis indicate the AFIT LAN will meet the school's expanding networking requirements. (Keywords: theses; computer communications; data transmission systems; communications networks; telecommunications).

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